PHASE FIVE
A NEW STATE OF MATTER

Why the cuprates? *That is the question.*

Cuprates, physicists would say, are certain ceramic metals made from copper, oxygen, and a variety of other elements. Like many metals, they are superconductors at temperatures close to absolute zero, but unlike *any other* metal, they remain superconducting at temperatures two to three times higher than their closest peer. The same physicists are baffled as to what it is about their atomic structure, their composition, or whatever else that enables them to create and sustain this high-temperature superconducting state?

Then there are the material phases. The elements making up a native cuprate are in certain proportions, which can be changed slightly by mixing in more of a particular element (doping). Doping often changes the electromagnetic properties of the metal, and depending on the degree of doping and the temperature, a cuprate will be in one of five material phases, or physical states: either a phase that exhibits an exotic type of magnetism (antiferromagnetism), the wonderfully bizarre high-temperature superconducting phase, an ordinary metal phase, a poorly understood metallic phase known as the pseudogap, or an equally poorly understood and strikingly weird metallic phase simply called a strange metal. These phases aren't unique; they are displayed by other (unconventional) metals, yet none of those materials are high-temperature superconductors. So why? Why the cuprates?

After 27 years of intense research, and more than 100,000 published research papers, condensed-matter physicists still can't answer that question. Neither can Los Alamos physicists Arkady Shekhter and Brad Ramshaw, but after conducting some pretty slick experiments this summer, the two scientists resolved a different longstanding question and gave theorists something solid to pin their hypotheses to. They showed conclusively that the pseudogap region of the cuprate phase diagram is a distinct phase of matter.

"For years, physicists thought that the pseudogap wasn't a distinct phase, just a region where the physical properties of the strange metal continued to evolve as the material cooled," says Shekhter. "The experimental evidence for a distinct phase was not compelling—the measured data had large uncertainties. With our measurement, there is no room to wiggle. Our data cannot be ignored."

Proof that the pseudogap was a fifth thermodynamic phase had immediate ramifications. It strongly suggested that the key to understanding high-temperature superconductivity would be found within the physics of the strange metallic state.

The backstory

In 1986, superconductors got high for the first time. Superconductors are materials that when cooled to extraordinarily low temperatures enter into a magical state in which electrons flow effortlessly through the material without loss of energy. Electric motors stay cool, power lines transport current with 100% efficiency, and electromagnets produce super-strong magnetic fields that can levitate anything from frogs to passenger trains. When electrical engineers daydream, superconducting circuits dance in their heads.

The problem was that a superconductor only superconducts when cooled below some critical temperature, denoted by T_c. The highest known T_c was about 23 degrees above absolute zero (23 kelvins, or 23 K). It required an unwieldy, expensive coolant—liquid helium—to reach that state of freeze. Consequently, superconductivity was a remarkable but seldom exploited phenomenon.

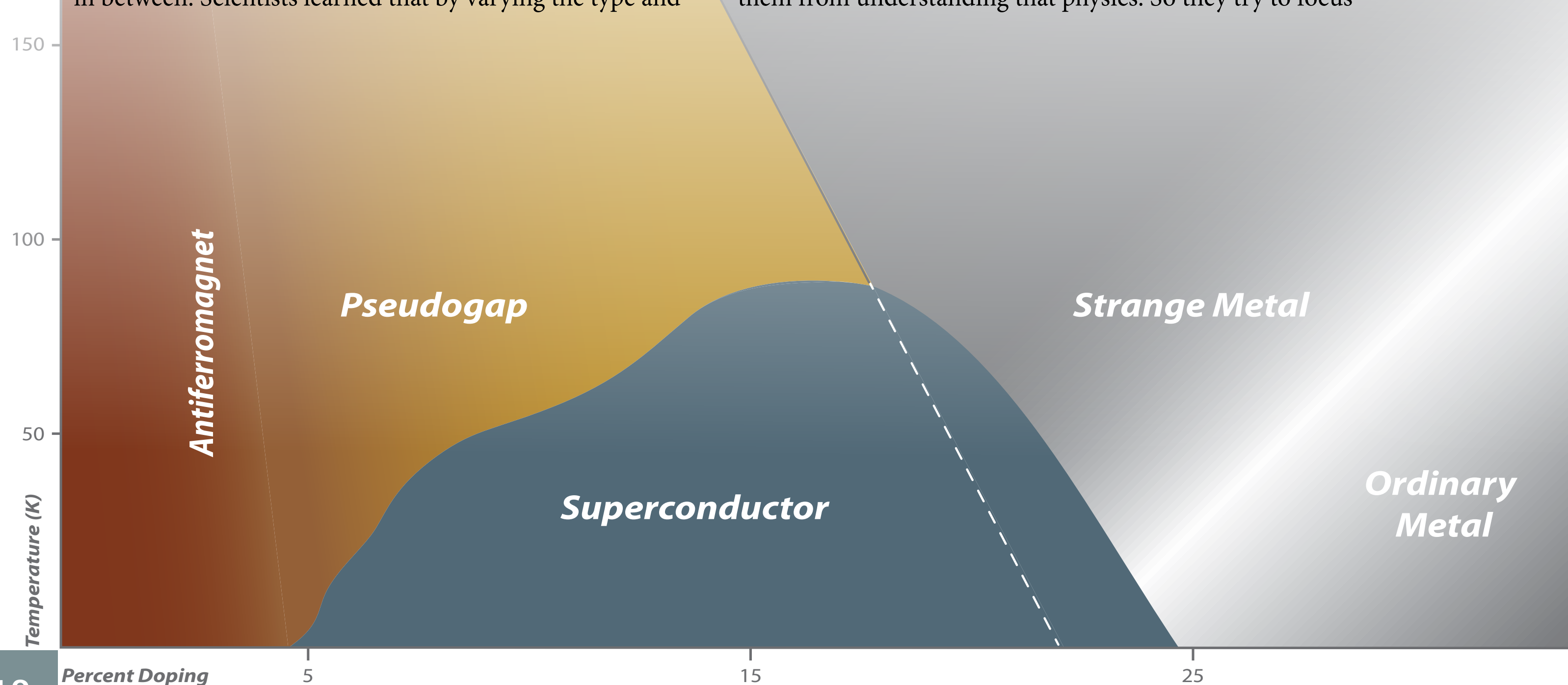
That looked like it was going to change in 1986, when out of nowhere came a cuprate with a T_c of 35 K. The materials community was deliriously happy. The new material had a layered structure, with copper and oxygen atoms forming flat layers and atoms of other elements sandwiched in between. Scientists learned that by varying the type and proportions of the other elements, they could change the critical temperature. Within two years, critical temperatures had climbed to 138 K, and scientists (and venture capitalists) could just about taste the fruits that would be harvested from a 300 K, room-temperature superconductor.

But there was no fruit. Other than by applying absurdly high pressures (hundreds of thousands of atmospheres), researchers could not increase T_c beyond 138 K. Furthermore, the cuprates were bizarre, and their superconductivity different from that manifested by conventional superconductors. They couldn't carry as much current as was hoped and would cease to be superconducting in even modest magnetic fields.

Most startling was their behavior at temperatures above T_c. The first measurements of cuprate single crystals showed that while the materials were metals, they were strange metals. For example, ordinary metals have a finite electrical resistivity at high temperatures, because thermal energy makes their atoms jiggle in place, which impedes the flow of electrons. The jiggling eases as the temperature drops, and the resistivity drops as described by "Landau's Fermi-liquid theory," which successfully explains the low-temperature behavior of conventional metals. But in the strange metal phase, the cuprates' resistivity didn't depend on jiggling atoms at all. That identified the cuprates as members of a class of metals known as "non-Fermi-liquid" metals. As they are the only metals to exhibit high-temperature superconductivity, they're really in a class of their own.

"The cuprates were unique," says Shekhter. "At that time in the mid-1980s, everyone believed they knew everything there was to know about metals. And suddenly there's this material exhibiting metallic behavior that we completely don't understand. It was a shock."

Theoretical physicists have a love-hate relationship with complex systems. They love the abundance of novel physics that such systems afford yet hate the complexity that prevents them from understanding that physics. So they try to focus



Brad Ramshaw (left) and Arkady Shekhter.

on one property and build the simplest model that captures the phenomena. As the model matures and becomes robust, they try and expand it to include more physics in the hope of explaining more and more phenomena with it.

Over time, many physicists came to view the strange metal phase as the core feature that distinguished the cuprates from other materials. While technologists continued to roam the high-T_c landscape, hoping to find the path to a room-temperature superconductor, many other scientists ignored the high-T_c superconducting phase altogether as they tried to understand the strange metal state.

"Physicists were completely stymied by this weird, strange metal state," says Ramshaw. "They had no idea who the players were that were responsible for its properties. Were they electrons, quasiparticles, strange couplings between spins and the lattice? No one had a clue."

Not knowing what to make of the strange metal state simply prompted more theories about how to make it. One of the more promising suggested that this solid phase was quantum-critical—the material's bulk properties depended on the details of how its quantum states evolved in time. This is not true for most phases. In a non-quantum-critical phase, the material is equally likely to be found in any of its available quantum states, so the physical properties only depend on what those states are, but not on how the system gets from one quantum state to the other.

If a quantum-critical phase were part of the cuprate's story, it would mean that as the temperature changed, a cuprate would undergo a phase transition between quantum-critical and non-quantum-critical phases. That transition should be observable at a specific temperature as a sharp change, or discontinuity, in many material properties.

Depending on the temperature and its specific composition (doping), a cuprate will be in one of five material phases. Undoped, the material is an insulator and an antiferromagnet, but it becomes metallic and an increasingly better metal as doping increases. Above 5 percent doping, the cuprate will exhibit superconductivity up to the critical temperature, T_c. At higher temperatures, it will either be in the pseudogap or strange metal phase. Above about 25 percent doping, the material is an ordinary metal. Shekhter and Ramshaw proved that the pseudogap was a distinct material phase.

The stage was set for Shekhter and Ramshaw to make measurements of a cuprate property and look for a discontinuity as the material cooled down. For the experimental method, they turned to an old workhorse—resonant ultrasound spectroscopy (RUS).

A new phase

Resonant ultrasound spectroscopy has been used for decades to study how the elastic properties of a crystalline material evolve with temperature. Briefly, one sandwiches a single crystal between two ultrasound transducers, one to vibrate the crystal at a chosen frequency and the other to detect the crystal response. At a resonance, the crystal vibrates strongly. By slowly changing the vibration frequency, one can find and measure all of the crystal's resonance frequencies, from which one determines the material's elastic constants. Changes in the elastic properties are tied to changes in the thermodynamic state of the material, including those associated with a phase transition.

Mentored in RUS by Los Alamos Fellow Albert Migliori, who looms large in the development of the technique, Shekhter and Ramshaw set about adapting it to work at low temperatures with very pure but uncomfortably small crystals. Small crystals meant small signal. Even at resonance, their response would be completely overwhelmed by the noisy vibrations of the surrounding environment. Experimental success boiled down to finding structural materials that were strong enough to hold the transducer-crystal sandwich, yet soft enough to isolate the sandwich from the rest of the vibrating world.

The right material turned out to be balsa wood, the stiff-yet-lightweight staple of the model airplane industry. The physicists began taking data, using a revolutionary new data acquisition and analysis technique they had developed specifically for this measurement. In theory, it would afford them significantly better temperature and frequency resolution.

"It worked," said Shekhter. "Our error bars were plus or minus 3 K, a factor of 10 tighter than people were able to do using other techniques."

While few now doubt that the pseudogap is a separate phase, and while the evidence for quantum-critical behavior is stronger, there's still no clear answer to what makes the cuprates special. It may be a simple answer, like the energy levels of copper are closer than any other transition element to the energy levels of oxygen, so a copper oxide, as opposed to any other elemental pairing, is the only combination wherein the electrons can arrange themselves as needed to produce strange metal states or high-T_c superconductivity. Or it may be something else. The only thing definitive is the question, "Why the cuprates?" LDRD

-Jay Schecker